Climate Warming & California's Water Future

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ABSTRACT

Few states depend more on climatic stability than California. While the California water system is designed fairly well to accommodate repeats of historical droughts in the near future, there is concern that California might not be able to easily accommodate major droughts in the more distant future, especially with the hydrologic consequences of significant climate warming. This study developed comprehensive surface and ground water hydrologies for 12 climate warming scenarios for California's inter-tied water system, as well as economic water demand estimates for urban and agricultural uses for estimates 2100 population levels. The most severe of these 12 climatic warming hydrologies was then employed with these 2100 economic water demands as inputs into an integrated economic-engineering optimization model of California's inter-tied water system (CALVIN). The results indicate the effects of population growth and climatic change on the performance of California's water system, as well as promising water management strategies to respond to these changes in supply and demand conditions over the coming century.

INTRODUCTION

In California, concern for climate change has increased in recent years with research on global climate change applied to California and as it has become apparent that California's climate has changed recently (Gleick and Chalecki 1999; Dettinger and Cayan 1995) and in recent millennia (Stine 1994). Several decades of studies have shown that California's climate is variable over history and in the present, is experiencing continuing sea level rise, and may experience significant climate warming. The potential effects of climate change on California have been widely discussed from a variety of perspectives (Wilkinson 2002; Gleick and Chalecki 1999; Lettenmaier and Sheer 1991). Forests, marine ecosystems, energy use, coastal erosion, water availability, flood control, and general water management issues have all been raised.

This study focuses on the likely effects of a range of climate warming estimates on the long-term performance and management of California's water system. We take a relatively comprehensive approach, looking at the entire inter-tied California water supply system, including ground and surface waters, agricultural and urban water demands, environmental flows, hydropower, and potential for managing water supply infrastructure to adapt to changes in hydrology caused by climate warming. We use an integrated economic-engineering optimization model of California's inter-tied water system called CALVIN (CALifornia Value Integrated Network), which has been developed for general water policy, planning, and operations studies (Jenkins et al 2001; Draper et al. 2003). This modeling approach allows us to look at how well the infrastructure of California water could adapt and respond to changes in climate, in the context of higher future populations, changes in land use, and changes in agricultural technology. Unlike traditional simulation modeling approaches, this economically optimized re-operation of the system to adapt to climate and other changes is not limited by present-day water system operating rules and water allocation policies, which by 2100 should be seen as archaic. Details of this climate change research effort can be found elsewhere (Lund et al. 2003).

METHOD

Many types of climate change can affect water and water management in California. This study examines climate warming, and neglects, for the time being climate variability, sea level rise, and other forms of climate change. Twelve climate warming hydrologies are examined to develop integrated statewide hydrologies covering changes in all major inflows to the California water system. For each climate warming scenario, permutations of historical flow changes were developed for six representative basins throughout California by researchers at LBNL (Miller, et al. 2001). These changes were used as index basins for 113 inflows to the CALVIN model, an extensive economic-engineering optimization model of California's inter-tied water system (Figure 1). This more comprehensive hydrology includes inflows from mountain streams, groundwater, and local streams, as well as reservoir evaporation for each of the twelve hydrologies. The gross implications of these twelve comprehensive changes in California's water availability are then estimated, including effects of forecasted changes in 2100 urban and agricultural water demands.

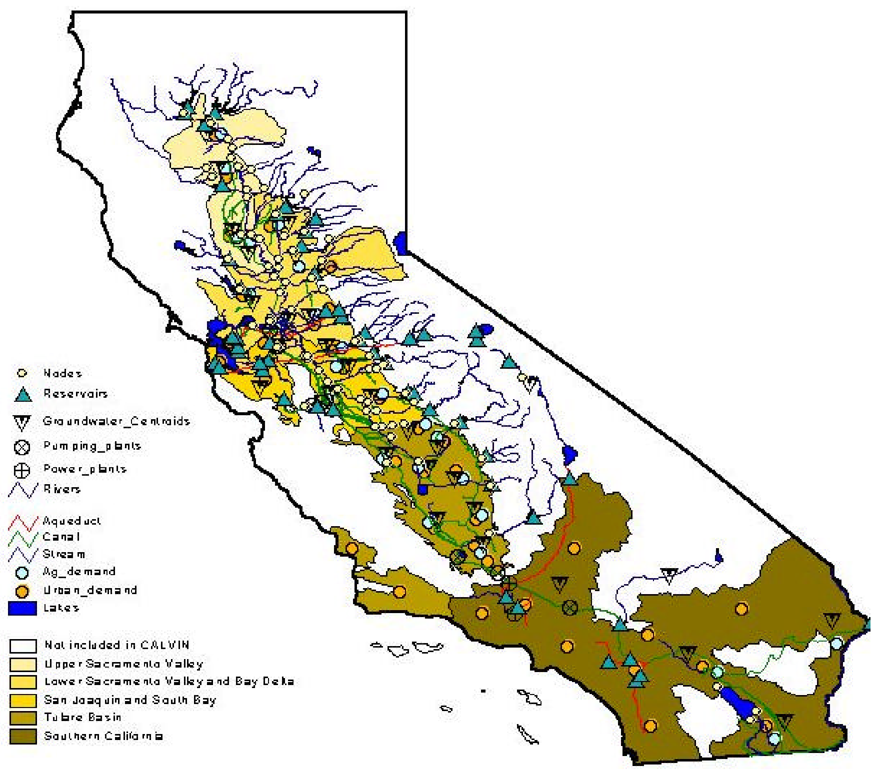

Figure 1. Demand Areas and Major Inflows and Facilities Represented in CALVIN

Owing to limited time and budget, only a few of these climate warming scenarios are modeled explicitly using the integrated economic-engineering optimization model (CALVIN). For this particular climate change study, several modifications were made to the CALVIN model:

- Changes in hydrology and water availability were made for surface and groundwater sources throughout the system to represent different climate warming scenarios.
- Estimates of year 2100 urban and agricultural economic water demands were used.
- Coastal areas were given unlimited access to sea water desalination at a constant unit cost of $1,400/acre-ft,
- Urban wastewater reuse was made available beyond 2020 levels at $1,000/acre-ft, up to 50% of urban return flows,
- Local well, pumping, and surface water diversion and connection and treatment facilities were expanded to allow access to purely local water bodies at appropriate costs.

The method employed for this study contributes several advances over previous efforts to understand the long-term effects of climate warming on California's water system, and long-term water management with climate change in general. These include:

- <u>Comprehensive hydrologic effects of climate warming</u>, from all major hydrologic inputs, including major streams, groundwater, and local streams, as well as reservoir evaporation. Groundwater, in particular, represents 30%-60% of California's water deliveries and 17% of natural inflows to the system.
- <u>Integrated consideration of groundwater storage</u>. Groundwater contributes about 75% of the storage used in California during major droughts.
- <u>Statewide impact assessment</u>. Previous explorations of climate change's implications for California have examined only a few isolated basins or one or two major water projects. However, California has a very integrated and extensive water management system. This system continues to be increasingly integrated in its planning and operations over time. Examination of the ability of this integrated system to respond to climate change is likely to requires examination of the entire system.
- <u>Economic-engineering perspective</u>. Water in itself is not important. It is the ability of water sources and a water management system to provide water for environmental, economic, and social purposes that is the relevant measure of the effect of climate change and adaptations to climate change. Traditional "yield"-based estimates of climate change effects do not provide results as meaningful as economic and delivery-reliability indicators of performance.
- <u>Integration of multiple responses</u>. Adaptation to climate change will not be through a single option, but a concert of many traditional and new water supply and management options. The CALVIN model explicitly represents and integrates a wide variety of response options.
- <u>Incorporation of future growth and change in water demands</u>. Climate change will have its greatest effects some decades from now. During this time, population growth and other changes in water demands are likely to exert major influences on how water is managed in California and how well this system performs.
- <u>Optimization of operations and management</u>. Most previous climate change impact studies on water management have been simulation-based. Since major climate changes are most likely to occur only after several decades, it seems unreasonable to employ current system operating rules in such studies. Fifty years from now, today's rules will be archaic. Since water management systems always have (and must) adapt to changing conditions, an optimization

approach seems more reasonable. The limitations of optimization seem less burdensome than the limitations of simulation for exploratory analysis of climate change policy and management problems.

RESULTS

The overall supply and demand results of this study appear below, followed by model results estimating the effects of climate and population change on the performance of California's inter-tied water supply system. More detailed results can be found in Lund et al. (2003).

Changes in Water Demands

An important aspect of future water management is future water demands. California's population continues to grow and its urban areas continue to expand, with likely implications for urban and agricultural water demands. Population growth in California is expected to continue from today's 32 million, to 45 million in 2020, to an estimated at 92 million for 2100. The demands in the inter-tied system (Table 1) represent about 90% of those in California.

Table 1. Applied Water Demands for California's Inter-tied Water System (maf/yr)

Use	2020 Water	2100 Water	2020-2100 Change
Urban	11.4	18.6	+7.2
Agricultural	27.8	25.1	-2.7
Total	**39.9**	**44.5**	**+4.5**

Changes in California's Water Supplies

The twelve climate warming scenarios examined, and their overall effects on water availability appear in Table 2. While these are merely raw hydrologic results, adjusted for groundwater storage effects, they indicate a wide range of potential water supply impacts on California's water supply system. These effects range from +4.1 maf/year to -9.4 maf/year.

Figure 2 shows the seasonal hydrologic streamflow results for the twelve warming scenarios for mountain rim inflows, about 72% of California system inflows. For all cases spring snowmelt is greatly decreased with climate warming, and winter flows are generally increased (except for some PCM scenarios). These results indicate the overall hydrologic effect of climate warming on inflows to California's water supplies. These overall trends have long been identified, based on single-basin studies (Lettenmaier and Gan 1990).

Table 2. Raw water availability estimates and changes (without adaptation, in maf/yr)

Climate Scenario	Average Annual Water Availability		Climate Scenario	Average Annual Water Availability	
	Volume maf	Change maf (%)		Volume maf	Change maf (%)
1) 1.5T 0%P	35.7	-2.1 (-5.5%)	7) HCM 2010-2039	41.9	4.1 (10.8%)
2) 1.5T 9%P	37.7	-0.1 (-0.4%)	8) HCM 2050-2079	40.5	2.7 (7.2%)
3) 3.0T 0%P	33.7	-4.1 (-10.9%)	9) HCM 2080-2099	42.4	4.6 (12.1%)
4) 3.0T 18%P	37.1	-0.8 (-2.0%)	10) PCM 2010-2039	35.7	-2.1 (-5.6%)
5) 5.0T 0%P	31.6	-6.2 (-16.5%)	11) PCM 2050-2079	32.9	-4.9 (-13.0%)
6) 5.0T 30%P	36.2	-1.6 (-4.3%)	12) PCM 2080-2099	28.5	-9.4 (-24.8%)
Historical	**37.8**	**0.0 (0.0%)**			

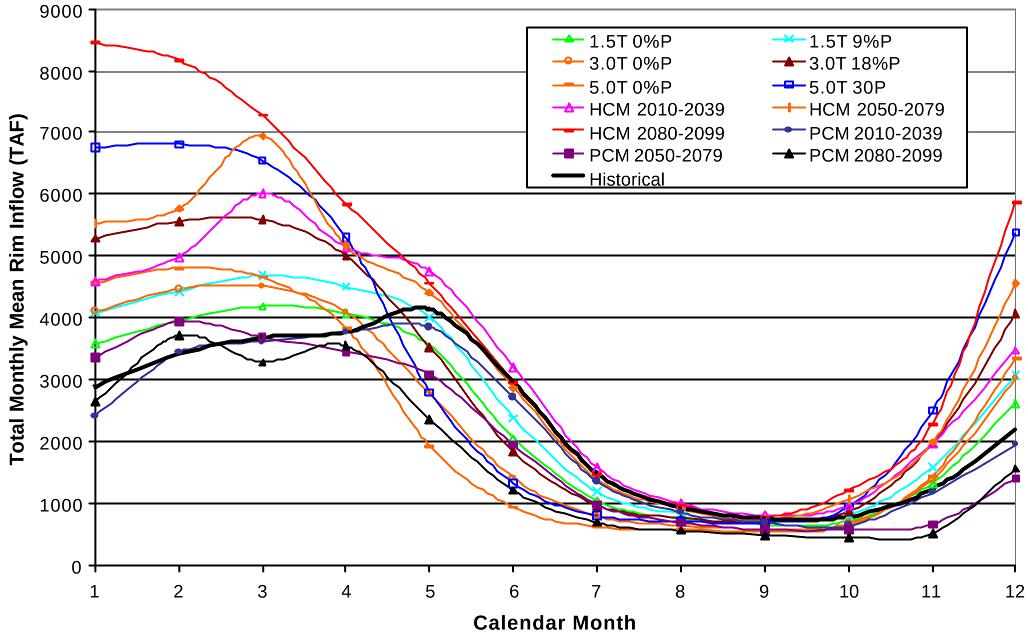

Figure 2. Monthly Mean Rim Inflows for the 12 Climate Scenarios & Historical Data

Adaptive Changes for Water Management

California has a diverse and complex water management system, which has considerable long-term physical flexibility. Californians are becoming increasingly adept at developing and integrating many diverse water supply and demand management options locally, regionally, and even statewide. The mix of options available to respond to climate change, population growth, and other challenges is only likely to increase in the future with development of water supply and demand management technologies, such as improved wastewater and desalination treatment methods and water use efficiency improvements.

Several statewide scenarios were run using the CALVIN economic-engineering optimization model to evaluate the potential impact of climate change on California with and without population growth and adaptation. The modeled scenarios presented here are:

- **Base 2020**: This run represents projected water supply operations and allocations in the year 2020, assuming continuation of current operation and allocation policies. This run was prepared for CALFED and extensively documented elsewhere (Jenkins et al, 2001; Draper, et al. 2003).
- **SWM 2020**: This run represents operations, allocations, and performance in the year 2020 assuming flexible and economically-driven operation and allocation policies. This optimized operation can be understood as representing operation under a statewide water market, or equivalent economically-driven operations (Jenkins et al, 2001; Draper, et al. 2003).
- **SWM 2100**: This run extends the SWM 2020 model and concept for 2100 water demands, but retains the same (historical) climate used in Base 2020 and SWM 2020.
- **PCM 2100**: Using the same 2100 water demands as SWM 2100, this run employs the dry and warm PCM 2100 climate warming hydrology.

Future Performance with Climate Warming

Population growth will have significant effects on the performance and water management of California's vast inter-tied system. Climate warming could have very large additional effects on this system, especially on its agricultural water users. These effects are summarized in Figures 3 and 4 which contain economic and volumetric effects for urban and agricultural water users. Overall the effects of population growth alone amount to roughly $800 million/year increases in scarcity costs over optimized 2020 operations (SWM2100), but are roughly comparable to Base2020 case costs, where current water operations and allocations are enshrined. Adding the worst climate warming scenario hydrology to the SWM2100 scenario (PCM2100) leads to greater water scarcity costs for urban users and much greater economic costs for agricultural users. Here agricultural user costs are overestimated, since modeled agricultural demands in the Central Valley are not yet fully corrected for urban land conversion, overestimating volumetric scarcity by roughly 2 maf/year and overestimating economic scarcity by a greater proportion.

Hydropower production from the major water supply reservoirs in the California system would not be greatly affected by population growth, but would be reduced by the PCM2100 climate warming scenario. Base2020 hydropower revenues average $160 million/year from the major water supply reservoirs, compared with $163million/year for SWM2100. However, the dry PCM2100 scenario reduces hydropower revenue 31% to $112 million/year.

CALVIN model results indicate several promising and capable adaptations to population growth and climate change (Lund et al. 2003). For PCM2100, these include market water transfers from agricultural to urban users, additional urban water conservation (~1 maf/yr), use of newer water reuse treatment (~1.5 maf/yr) and sea water desalination technologies (~0.2 maf/yr), increased conjunctive use of ground and surface waters, and several million acre-feet/year of reductions in agricultural use due to water transfers, land fallowing, and urbanization of agricultural land. All of these indicate a much more tightly managed (and controversial) California water system, where water is increasingly valuable because it is increasingly scarce. But, while costly, the prosperity of California's overall economy and society should not be seriously threatened by these scenarios.

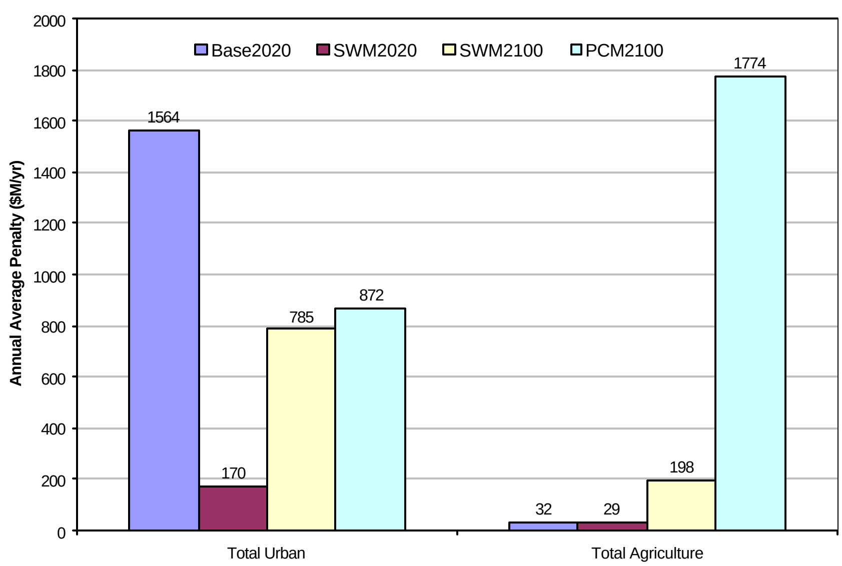

Figure 3. Average Annual Economic Scarcity Cost by Sector

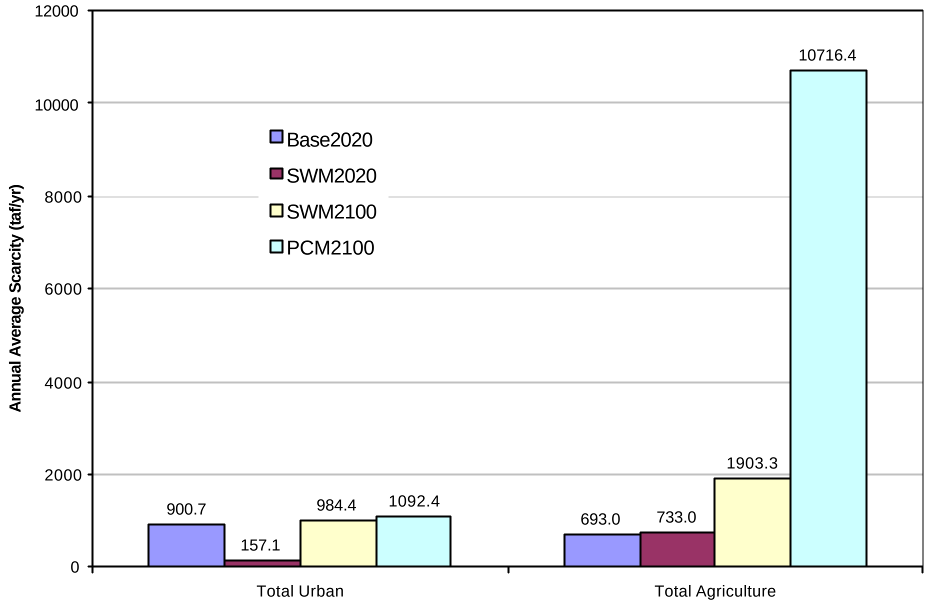

Figure 4. Total Volumetric Scarcity

Some operational results for overall surface and groundwater storage in California appear in Figures 5 and 6. Most storage available and used within the California water system is underground. As appears in the figures, over two thirds of the storage used between wet and dry periods takes the form of groundwater. The PCM2100 scenario provides noticeably more challenge for the surface water system overall. All optimized and future scenarios make greater use of groundwater storage for drought management than current policies (Base2020).

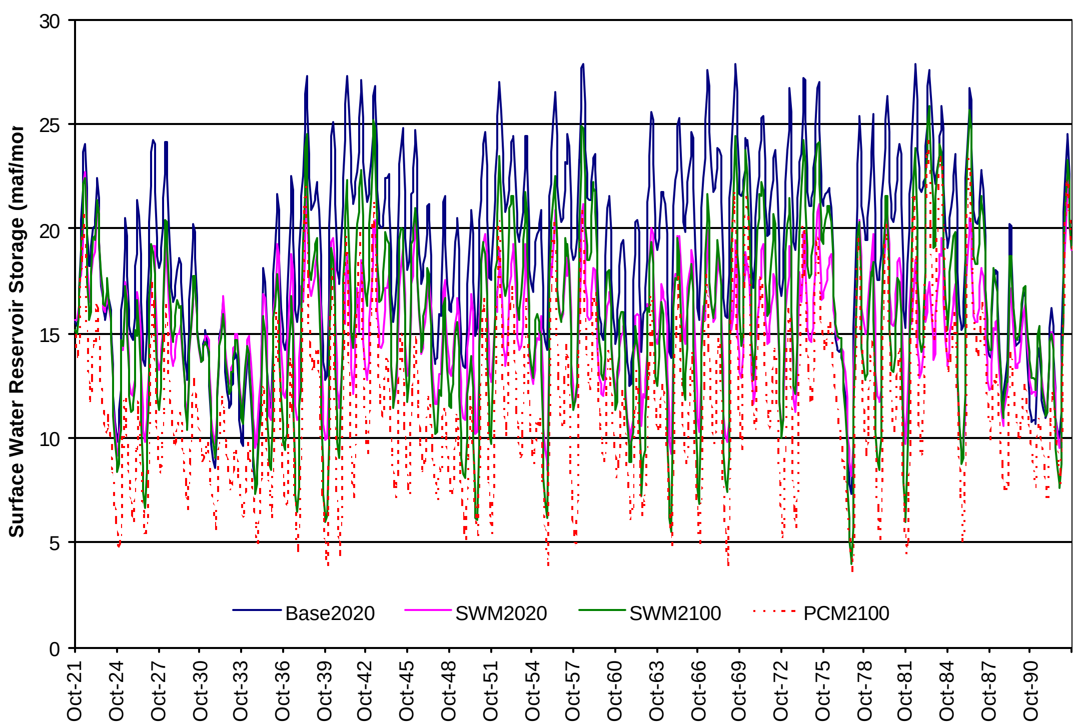

Figure 5. Statewide Surface Water Storage over 72-year Period

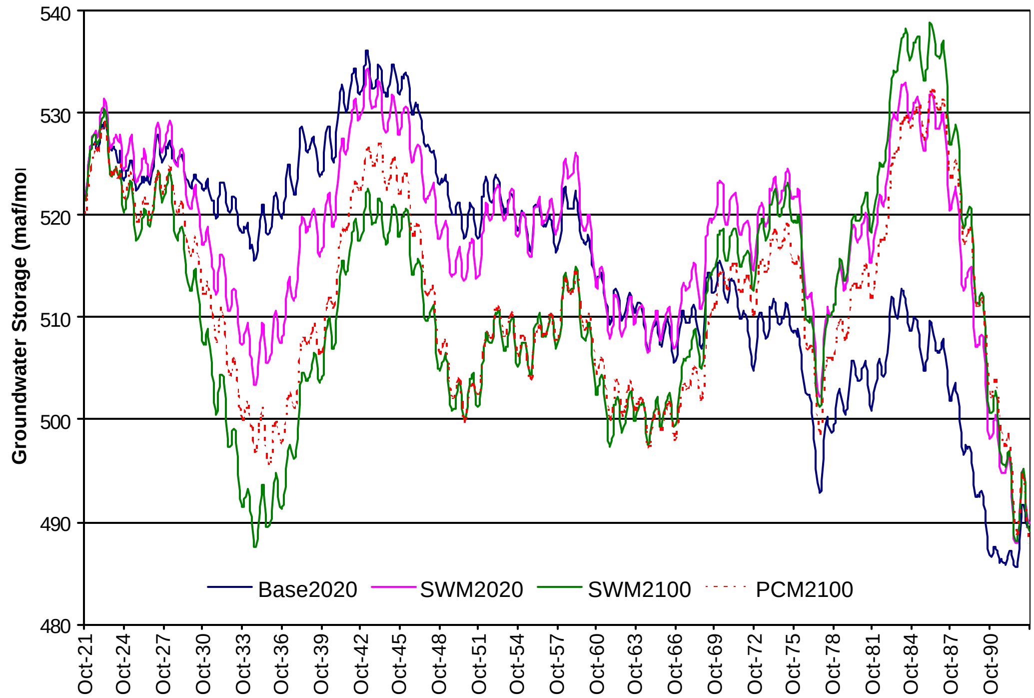

Figure 6. Groundwater Storage over the 72-year Period

Population growth and climate warming also impose serious environmental challenges. While in 2020 and with 2100 population growth alone, it appears possible to comply with environmental flow and delivery requirements, some small reductions in environmental flows are required for the PCM2100 scenario. However, increased water demands and decreased water availability do raise substantially the costs of environmental requirements to urban, agricultural, and hydropower users, as shown in Figure 7 and Table 3. Increased economic costs of complying with environmental requirements could raise incentives to dispute and evade such requirements, as well as incentives to creatively address environmental demands.

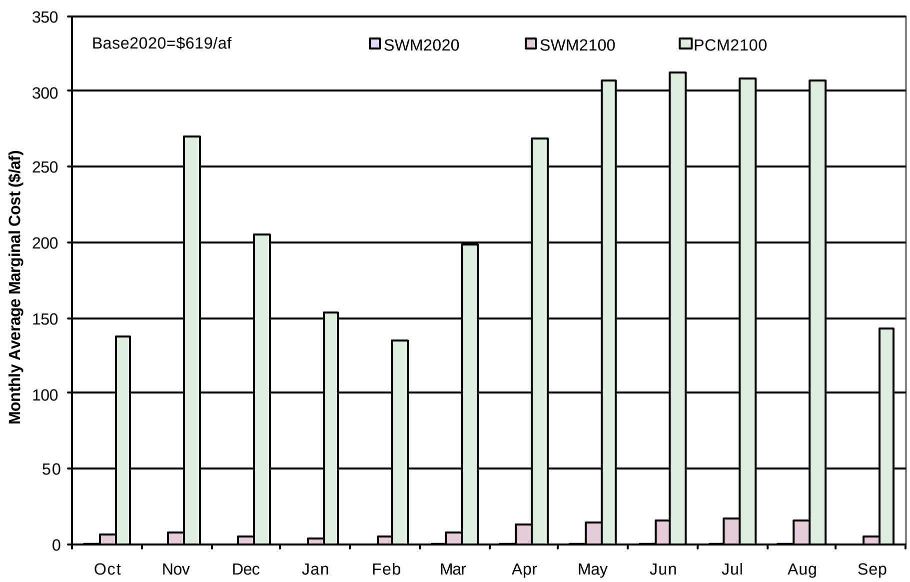

Figure 7. Monthly Shadow Costs of Delta Outflow Requirements

Table 3. Average Shadow Costs of Selected Environmental Requirements ($/af)

	SWM2020	SWM2100	PCM2100
Minimum Instream Flows			
Sacramento River	0.2	1.2	25.3
Feather River	0.1	1.6	35.5
American River	0.0	4.1	42.3
Mokelumne River	0.1	20.7	332.0
Yuba River	0.0	0.0	1.6
Stanislaus River	1.1	6.1	64.0
Tuolumne River	0.5	5.6	55.4
Mono Lake Inflows	819.0	1254.5	1301.0
Owens Lake Dust Mitigation	610.4	1019.1	1046.1
Refuges			
SacWestRefuge	0.3	11.1	231.1
SacEastRefuge	0.1	0.8	4.7
Volta Refuges	18.6	38.2	311.0
San Joaquin/Mendota Refuges	14.7	32.6	249.8
Pixley	24.8	50.6	339.7
Kern	33.4	57.0	377.1
Delta Outflow	0.1	9.7	229.0

CONCLUSIONS

The main conclusions of this work so far are:

1) Methodologically, it is possible, reasonable, and desirable to include a wider range of hydrologic effects, changes in population and water demands, and changes in system operations in impact and adaptation studies of climate change than has been customary. Overall, including such aspects in climate change studies provides more useful and realistic results for policy, planning, and public education purposes.

2) A wide range of climate warming scenarios for California shows significant increases in wet season flows and significant decreases in spring snowmelt. This conclusion, confirming many earlier studies, is made more generally and quantitatively for California's major water sources. The magnitude of climate warming's effect on water supplies can be comparable to water demand increases from population growth in the coming century.

3) California's water system can adapt to the population growth and climate changes modeled, which are fairly severe. This adaptation will be costly in absolute terms, but, if properly managed, should not threaten the fundamental prosperity of California's economy or society. The water management costs are a tiny proportion of California's current economy.

4) While adaptation can be successful overall, the challenges are formidable. Even with new technologies for water supply, treatment, and water use efficiency, widespread implementation of water transfers and conjunctive use, coordinated operation of reservoirs, improved flow forecasting, and the close cooperation of local, regional, state, and federal government, the costs will be high and there will be much less "slack" in the system compared to current operations and expectations. The economic implications of water

management controversies will be greater, motivating greater intensity in water conflicts, unless management institutions can devise more efficient and flexible mechanisms and configurations for managing water in the coming century.

5) The limitations of this kind of study are considerable, but the qualitative implications seem clear. It behooves us to carefully consider and develop a variety of promising infrastructure, management, and governance options to allow California and other regions to respond more effectively to major challenges of all sorts in the future.

REFERENCES

Dettinger, M. D. and D. R. Cayan (1995). "Large-Scale Atmospheric Forcing of Recent Trends toward Early Snowmelt Runoff in California." *Journal of Climate* 8(3): 606–623.

Draper, A.J., M.W. Jenkins, K.W. Kirby, J.R. Lund, and R.E. Howitt (2003), "Economic-Engineering Optimization for California Water Management," *Journal of Water Resources Planning and Management*, ASCE, May.

Gleick, P.H. and E.L. Chalecki (1999), "The Impact of Climatic Changes for Water Resources of the Colorado and Sacramento-San Joaquin River Systems," *Journal of the American Water Resources Association*, Vo. 35, No. 6, pp. 1429-1441.

Jenkins, et al. (2001), *Improving California water management: optimizing value and flexibility.* Report No. 01-1, Center for Environmental and Water Resources Engineering, University of California, Davis, CA. http://cee.engr.ucdavis.edu/faculty/lund/CALVIN/

Lettenmaier D. P. and Gan, T. Y. (1990), Hydrologic Sensitivity of the Sacramento-San Joaquin River Basin, California, to Global Warming. *Water Resources Research*, 26(1), 69-86.

Lettenmaier D. P. and D.P. Sheer (1991), Cimatic Sensitivity of California Water Resources, *Journal of Water Resources Planning and Management*, Vol. 117, No. 1, Jan/Feb, pp. 108-125.

Lund, J.R., et al. (2003), *Talking About the Weather: Climate Warming & California's Water Future*, Center for Environmental and Water Resources Engineering, University of California, Davis, CA. http://cee.engr.ucdavis.edu/faculty/lund/CALVIN/

Miller, N. L., Bashford, K. E., and Strem, E. (2001) Climate Change Sensitivity Study of California Hydrology. A report to the California Energy Commission, LBNL Technical Report No. 49110, Berkeley, CA, November, 2001.

Stine, S. (1994) Extreme and persistent drought in California and Patagonia during medieval time. *Nature*: 369, 546-9.

Wilkinson, R. (2002), *Preparing for a Changing Climate: The potential consequences of climate variability and change – California*, A report of the California Regional Assessment Group for the U.S. Global Change Research Program, Santa Barbara, CA.

